Fermi National Accelerator Laboratory

Masses and Lifetimes of B Hadrons

I. Joseph Kroll

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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I. JOSEPH KROLL

Fermilab
P. O. Box 500
Batavia, IL, 60510, U.S.A.
E-mail: kroll@fnal.gov

Abstract

The latest measurements of the masses and lifetimes of weakly decaying B hadrons from experiments at e^+e^- and $p\bar{p}$ colliders are presented. These measurements include the lifetimes of the $\bar{B}^0$, $\bar{B}^0_s$, B^-, and b baryons, as well as searches for the B_c meson. The observation of B^*, p-wave B mesons (B^{**}), and excited b baryons using inclusive and exclusive B hadron reconstruction are discussed. Results on b quark flavour tagging are given.

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ABSTRACT

The latest measurements of the masses and lifetimes of weakly decaying B hadrons from experiments at e^+e^- and $p\bar{p}$ colliders are presented. These measurements include the lifetimes of the $\bar{B}^0$, $\bar{B}^0_s$, B^-, and b baryons, as well as searches for the B_c meson. The observation of B^*, p-wave B mesons (B^{**}), and excited b baryons using inclusive and exclusive B hadron reconstruction are discussed. Results on b quark flavour tagging are given.

1. Introduction

The masses and lifetimes of B hadrons are fundamental properties of these particles and are needed to determine other quantities such as V_{cb}[1], as well as Δm_d and Δm_s[2]. Their values can be used to test theoretical models of heavy quark decay[3]. For example, the $1/m_Q$ expansion in QCD predicts lifetime differences for the different species of B hadrons[4]. Heavy Quark Effective Theory (HQET) predicts that the mass differences between excited and ground states (*e.g.* between B and B^*) should be independent of the heavy quark mass, m_Q, as $\Lambda_{QCD}/m_Q \to 0$. If these models do not predict the experimental observables, then perhaps the models are not as reliable as we believe. Finally, the large top quark mass implies that the top quark decays weakly before it hadronizes. The b quark is the heaviest quark with which we can study these heavy flavour models.

The experimental results presented in this review come from e^+e^- collisions at the Z^0 resonance (LEP at CERN and SLC at SLAC) and from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV (the Tevatron at Fermilab).

On the Z^0 resonance, $b\bar{b}$ production is 22% of the hadronic cross section[5]. The experimental trigger efficiency and selection efficiency for hadronic events are very close to 100%. The B hadrons have a large Lorentz boost ($\beta\gamma$): the average value is 6 (*i.e.* a momentum of 30 GeV/c), and the mean distance travelled by a B hadron is 3 mm.

At the Tevatron, the inclusive B hadron cross section is 37μb[6], which is very large, but the inelastic cross section[7] is three orders of magnitude larger. Specialized triggers are required to extract the B hadron signal. The triggers used in the results presented in this review are (1) a dimuon trigger that triggers on the process $B \to J/\psi + X, J/\psi \to \mu^+\mu^-$, and (2) an inclusive lepton trigger, which is based on the semileptonic decays of B hadrons: $B \to \ell\nu X, \ell = e$ or μ. The average transverse mo-

mentum (with respect to the colliding beam axis) of the B hadrons from the dimuon trigger is 10 GeV/c, and the average transverse momentum from the inclusive lepton trigger is 20 GeV/c. Despite the much larger center-of-mass energy, the B hadrons studied at the Tevatron are softer than the B hadrons produced on the Z^0 resonance.

The data samples used for the results presented in this review are summarized in Table 1. This Table also summarizes the characteristics of the detectors and accelerators crucial to the lifetime measurements, namely the silicon strip and pixel vertex detectors and the beam profiles. The small beam size and close proximity of the first layer of the vertex detector allow SLD to make competitive lifetime measurements despite a much smaller data sample than the LEP experiments.

Table 1. A summary of the data samples used for the results presented in this review. The Table also includes information about the silicon strip and pixel vertex detectors and the sizes of the beam envelopes at the different accelerators. The data sample size for LEP is the range of sample sizes of the four experiments. The SLD pixel detector has four layers, but the average number of hits per track is 2.3. The coordinates are cylindrical, with the z axis corresponding to the beam line.

Detector	LEP	SLD	CDF
Data Sample	$3.1 - 3.7 \times 10^6$ $Z^0 \to$ hadrons	1.5×10^5 $Z^0 \to$ hadrons	120 pb^{-1}
Vertex Detector	Silicon strip $r\phi$ and rz	CCD (Pixel) $r\phi$ and rz	Silicon Strip $r\phi$ only
Beam Size σ_x σ_y σ_z	100–160 μm 5–10 μm 7 mm	2 μm 1 μm 0.7 mm	35–40 μm 35–40 μm 30 cm
vertex det. inner radius	6 cm	2.5 cm	3 cm
# layers	2–3	4	4

2. Masses and Lifetimes of Weakly-decaying B Hadrons

There are four weakly decaying mesons containing b quarks: $\bar{B}^0$ ($b\bar{d}$), B^- ($b\bar{u}$), $\bar{B}_s^0$ ($b\bar{s}$), and B_c^- ($b\bar{c}$); and four predicted weakly decaying baryons: Λ_b^0 (bud), Ξ_b^0 (bsu), Ξ_b^- (bsd), and Ω_b^- (bss).[a] Only the $\bar{B}^0$, B^-, $\bar{B}_s^0$, and Λ_b^0 have been firmly established experimentally. In the spectator model of the decay of a hadron containing a b quark, the lifetime is given by

$$, = 1/\tau = \frac{G_F^2 m_b^5}{192\pi^3} \cdot |V_{bc}|^2 \times \mathcal{F}_{ps},$$

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[a] All references to particles containing a b quark also imply the equivalent particles containing a $\bar{b}$ quark, and all decay sequences imply the charge conjugate process as well.

where $\mathcal{F}_{ps}$ is a phase-space factor (there is also a term with $|V_{bu}|^2$, which is small and has been neglected). All B hadrons are predicted to have equal lifetimes. These hadrons also have equal semileptonic branching fractions, since the partial width $\Gamma_\ell = \Gamma(b \to \ell\nu c)$ is equal for all B hadrons, and therefore $B(b \to \ell\nu c) = \Gamma_\ell/\Gamma$ is the same for all B hadrons.

The spectator model failed in the prediction of the equality of the lifetimes of the charmed hadrons:

$$\tau(D^+) \approx 2.5\tau(D^0) \approx 2.5\tau(D_s) \approx 5.0\tau(\Lambda_c).$$

These lifetime differences are attributed to nonspectator effects such as final state interference, annihilation diagrams, and helicity suppression. Applying these same ideas to B hadrons results in the lifetime hierarchy:

$$\tau(\Lambda_b) < \tau(\bar{B}^0) \approx \tau(\bar{B}_s^0) < \tau(B^-).$$

A QCD expansion in powers of $1/m_b$ yields quantitative predictions[4]:

$$\frac{\tau(B^-)}{\tau(\bar{B}^0)} = 1 + 0.05 \cdot \left[\frac{f_b}{200 MeV}\right]^2,$$

$$\frac{\tau(\bar{B}_s^0)}{\tau(\bar{B}^0)} \approx 1,$$

$$\frac{\tau(\Lambda_b)}{\tau(\bar{B}^0)} \approx 0.9,$$

where f_b is the B meson form factor (expected to be 200 to 250 MeV).

There have been two types of B hadron lifetime measurements: (1) average and (2) species specific. The average is the lifetime of the produced mixture of weakly decaying B hadrons. The usual assumption about this mixture is 40% B^-, 40% $\bar{B}^0$, 12% $\bar{B}_s^0$ and 8% b baryons. The species specific lifetimes require a fairly pure signature of a specific B hadron, e.g. $\bar{B}^0 \to J/\psi \bar{K}^{*0}$.

Two methods have been employed to make these lifetime measurements. The first is based on the signed impact parameter δ, which is illustrated in Figure 1. The Figure illustrates a B hadron, which is produced at the collision point, propagates away from the point where it is produced, and then decays. The reconstructed trajectories of charged particles coming from the B hadron decay are extrapolated back to the collision point. The distance of closest approach of these extrapolated trajectories to this collision point is the impact parameter. It can be reconstructed in two-dimensions (the plane perpendicular to the beam line) or three-dimensions. The impact parameter has a positive (negative) sign if the extrapolated track trajectory crosses the B hadron flight direction in front of (behind) the collision point. In the example depicted in the Figure, the sign is positive. A negative impact parameter
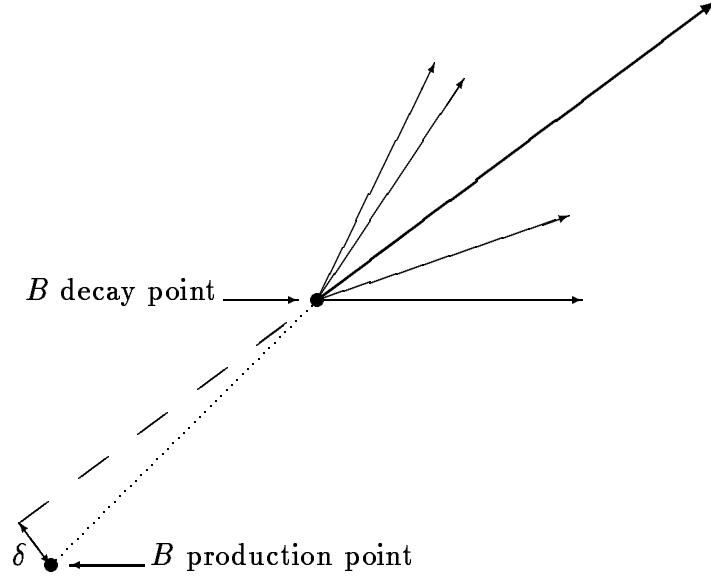
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B decay point

δ B production point

Fig. 1. The definition of the signed-impact parameter δ.

can arise due to either a decay product that goes backwards or due to resolution effects, either in the determination of the trajectory of the decay product or in the determination of the B hadron flight direction. The average impact parameter is proportional to the lifetime of the B hadron. The advantage of using the impact parameter is that it is fairly insensitive to the B hadron boost: a B hadron with a larger Lorentz boost will travel farther, but the decay products come out at a smaller angle, leaving δ unchanged. To extract the lifetime, a Monte Carlo model is used to reproduce the observed impact parameter distribution as a function of the B hadron lifetime. The sign of the impact parameter is important for the Monte Carlo modelling: since the negative part of the impact parameter distribution is dominated by resolution effects, it provides a means to control the resolution in the Monte Carlo model. Typically impact parameter measurements are made using leptons (electrons or muons) from B hadron semileptonic decays; in fact, the signed impact parameter of leptons was the method employed to make the first measurements[8] of the b lifetime.

The second method for measuring lifetimes is based on the decay length, which is the distance from the B hadron production point to the B hadron decay point. The decay length L is related to the lifetime $c\tau$ by the Lorentz boost $\beta\gamma$:

$$L = \beta\gamma c\tau.$$

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Unlike the impact parameter method, it is necessary to know the boost value. In the case of a fully reconstructed B hadron decay, the determination of the boost value is straightforward:

$$\beta\gamma = p_B/m_B,$$

where p_B is the B hadron momentum and m_B is the B hadron mass.

2.1. Average Lifetime of B Hadrons

Measurements of the average B hadron lifetime have been made using both the impact parameter method and the decay length method. The results are summarized in Table 2.

Table 2. Summary of average B hadron lifetimes. The first error is the statistical error, and the second error is the systematic error. For impact parameter methods, 2D and 3D indicate whether the analysis is performed in two-dimensions or three-dimensions.

Experiment	Method	Data Set	Result (psec)	Reference
ALEPH	lepton δ (3D)	91–93	$1.533 \pm 0.013 \pm 0.022$	9
ALEPH	dipole	91	$1.511 \pm 0.022 \pm 0.078$	10
DELPHI	hadron δ (2D)	91–92	$1.542 \pm 0.021 \pm 0.045$	11
DELPHI	hadron vertex	91–93	$1.600 \pm 0.010 \pm 0.028$	12
L3	lepton δ (2D)	90–91	$1.535 \pm 0.035 \pm 0.028$	13
OPAL	lepton δ (2D)	90–91	$1.523 \pm 0.034 \pm 0.038$	14
SLD	hadron vertex	93	$1.564 \pm 0.030 \pm 0.036$	15
CDF	J/ψ vertex	Run 1a	$1.46 \pm 0.06 \pm 0.06$	16

Four measurements based on impact parameter (δ) are reported. Three are based on the impact parameter of leptons. The lepton selections yield samples that have a B hadron purity between 85% and 95%. The dominant systematic errors are due to the modelling of b quark fragmentation and B hadron decay, the understanding of the impact parameter resolution, and the background shape.

Four measurements based on reconstructed decay vertices are reported. DELPHI and SLD reconstruct the decay length of vertices found in hadronic Z^0 decays. ALEPH uses the so-called dipole method, which measures the distance between the B vertex and the $\bar{B}$ vertex. This method does not rely on the determination of the production point of the B and $\bar{B}$. Finally, CDF uses the vertex reconstructed from $J/\psi \rightarrow \mu^+\mu^-$ coming from $B \rightarrow J/\psi + X$ decays (ALEPH, DELPHI, and OPAL also have results coming from this signature, but the statistics are much lower than the CDF result).

These average lifetime measurements must be compared with caution. The different methods may select different mixtures of B hadrons and therefore might not be measuring the same average. For example, the measurements based on lepton impact parameter are an average of the mixture of B hadrons produced times their

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semileptonic branching fractions:

$$< \tau >= \sum_{i=species} f(b \to B_i)B(B_i \to \ell)\tau(B_i).$$

Average lifetimes based on vertices may have biases favouring neutral or charged B hadrons depending whether the minimum number of tracks required for a vertex is even or odd. Because of the potential differences between methods, an average of the measurements is not given. The two most precise measurements are from ALEPH[9] (using lepton impact parameter) and DELPHI[12] (using hadronic decay vertices). The DELPHI systematic error is dominated by uncertainties in b quark fragmentation and Monte Carlo statistics. Both measurements have total errors of less than 2%, but they differ by 1.7σ.

2.2. $\bar{B}^0$ and B^-

Three types of signatures have been used to measure species specific lifetimes:

1. *Fully reconstructed decays:* all decay products of the B hadron are detected and the B hadron is fully reconstructed. The disadvantage of this approach is the small branching fractions to particular final states yield low statistics samples. The advantages are the straightforward determination of the decay length, the Lorentz boost, and the background (from mass distribution sidebands).

2. *Partially reconstructed decays:* these final states typically consist of a lepton and a fully reconstructed charmed hadron. The advantage of this method is significantly larger statistics than fully reconstructed decays, but the disadvantages include systematics in determining the Lorentz boost, larger backgrounds, contamination from other species of B hadrons, and reconstructing the decay length.

3. *Inclusive vertex with charge determination:* this technique has been used on the Z^0 resonance to determine the $\bar{B}^0$ and B^- lifetimes. The B hadron decay vertex is reconstructed, and the charge of the B hadron is determined from the sum of the charges associated to the B vertex. Monte Carlo simulation is needed to determine how well the charged and neutral states are separated and the effect of $\bar{B}_s^0$ and b baryons.

Two experiments have reported lifetimes of $\bar{B}^0$ and B^- based on exclusive decays. CDF exploits a $J/\psi \to \mu^+\mu^-$ trigger to reconstruct large samples of $B \to J/\psi K$. From a data sample of 67 pb^{-1}, they have a signal of 524 ± 29 B^-, predominantly from $B^- \to J/\psi K^-$, and 285 ± 21 $\bar{B}^0$, predominantly from $B^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi K_s^0$. The ALEPH experiment takes advantage of good particle identification (dE/dx) and excellent charged particle momentum resolution to reconstruct 94 B^-

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candidates and 121 $\bar{B}^0$ candidates from a large number of final states[17] using 3×10^6 hadronic Z^0 decays from 1991 to 1994. The measured lifetimes are reported in Table 4 ($\bar{B}^0$) and Table 5 (B^-).

Four experiments (ALEPH, DELPHI, OPAL, CDF) have reported lifetimes of $\bar{B}^0$ and B^- based on partially reconstructed exclusive final states. The signature is $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ and $\bar{B}^0 \to D^+\ell^-\bar{\nu}$ for the neutral B meson, and $B^- \to D^0\ell^-\bar{\nu}$ for the charged B meson.

Figure 2 depicts a specific example of one of these decays: $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ with $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$, and serves to illustrate several important features of lifetime measurements based on this type of signature.

- The lepton and the charged K have the same charge. Candidates in which the lepton and charged K have opposite charge provide a sample that can be used to study the combinatorial background.

- Requirements on kinematic properties of the lepton such as the momentum of the lepton and the component of the momentum of the lepton perpendicular to the B hadron momentum (p_t^{rel}) are used to suppress backgrounds from misidentified leptons and leptons not arising from B hadron semileptonic decays.

- Since the momentum of the neutrino is not directly measured, the Lorentz boost of the B hadron must be estimated from the observed lepton and D meson. This estimation requires input from Monte Carlo models and the typical resolution on $\beta\gamma$ is $\sigma_{\beta\gamma} \approx 15\%$. Alternatively, on the Z^0 resonance, the energy of the neutrino can be estimated from the observed momentum imbalance of the event. With this approach, the ALEPH experiment achieves a resolution on the neutrino energy of $\sigma(E_\nu) \approx 3$ GeV.

- The D^0 is fully reconstructed and is extrapolated back to the point where it intersects with the lepton to form the B decay vertex. The D^0 decay vertex is measured as well, so the D^0 lifetime can be measured and used to search for biases in the lifetime determination. The typical resolution on the D decay length is $\sigma(L_D) \sim L_D$. In contrast, the resolution on the decay length of the B hadron is typically an order of magnitude less than the decay length itself, $\sigma(L_B) \sim L_B/10$. Exact modelling of the decay length resolution is not crucial and is not a dominant systematic error.

The $D^{*+}\ell^-\bar{\nu}$, $D^+\ell^-\bar{\nu}$ sample and the $D^0\ell^-\bar{\nu}$ sample do not comprise unique samples of $\bar{B}^0$ and B^- mesons: there is some cross-contamination between the two B meson types. There is a small contamination in the B^- sample from $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ with $D^{*+} \to D^0\pi^+$, and the soft pion is not detected. This contamination is small, because the detection efficiency for the soft pion is greater than 85% in all experiments. The more serious source of cross-contamination comes from semileptonic decays involving

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D^{**} and nonresonant $D\pi$. For example, the decay sequence $\bar{B}^0 \to D^{**+}\ell^-\bar{\nu}$ with $D^{**+} \to D^0\pi^+$ will be classified as a "$D^0\ell^-\bar{\nu}$" final state and interpreted as coming from a B^-. The fraction of semileptonic decays involving a D^{**} and nonresonant $D\pi$ is approximately 30–40%. In these analyses, the fraction of decays involving D^{**} is assumed to be $f^{**} = 36 \pm 12\%$. If the ratio of lifetimes $\tau(B^-)/\tau(B^0)$ is unity, then the $D^0\ell^-\bar{\nu}$ sample is typically 80–90% B^- and the $D^{(*)}\ell^-\bar{\nu}$ sample is typically 70–80% B^0. In the future, measurements of f^{**} such as those presented by the ALEPH[25] and OPAL[26] collaborations will be used to reduce the systematic error due to cross-contamination between the partially reconstructed $\bar{B}^0$ and B^- samples.
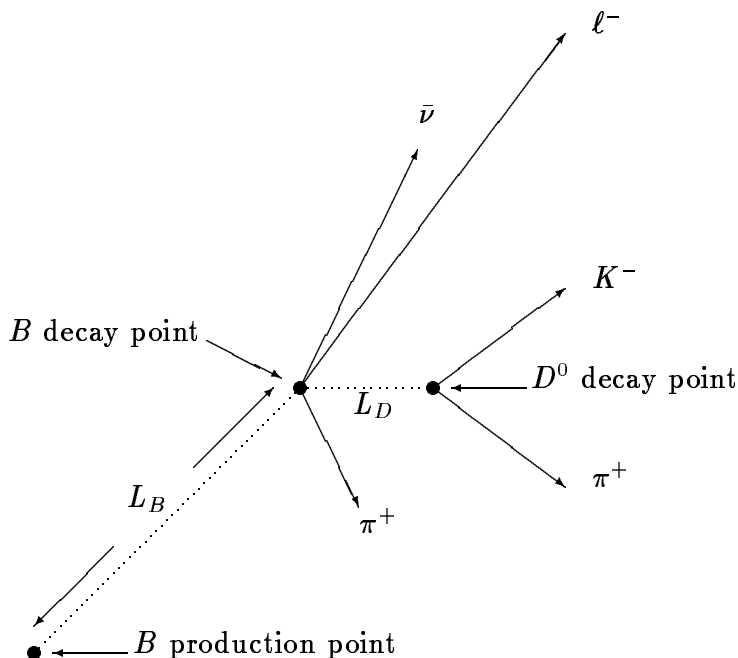

Fig. 2. Illustration of the decay $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ with $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$.

There are two sources of backgrounds in these partially reconstructed final states: (1) physics backgrounds from decays such as $B \to D_s^- D$, followed by $D_s^- \to \ell^-\bar{\nu}X$, and (2) combinatoric background that results from a misidentified lepton combined with a real D or a real lepton combined with a combinatorial D. The physics background is suppressed by kinematic requirements on the lepton and is small. The combinatorial background is suppressed using particle identification and kinematic requirements, but is often the source of the largest systematic error. The lifetime distribution of the background can be determined from the data by using the D sideband distributions and lepton D combinations that have the wrong charge correlation.

Table 3 reports the signal sizes from the various experiments and the lifetime

measurements are given in Table 4 and Table 5. The statistics of the signals from these semi-exclusive final states are substantially larger than the statistics of the fully reconstructed decays.

Table 4 lists one other measurement of $\tau(\bar{B}^0)$ based on partially reconstructed $\bar{B}^0 \to \pi_B^- D^{*+}X$ decays. This result comes from the ALEPH experiment and is based on the decay chain: $\bar{B}^0 \to \pi_B^- D^{*+}X$, $D^{*+} \to D^0 \pi_D^+$. The observed $\pi_B^- \pi_D^+$ system is used to isolate the signal and to determine the $\bar{B}^0$ momentum and decay point.

Table 3. Summary of the lepton plus D signal statistics (background subtracted) for the $\bar{B}^0$ and B^- lifetime measurements. The number of Z^0's means hadronic Z^0 decays.

Experiment	Data Sample	B^0	B^-	Ref.
ALEPH	$3 \times 10^6 Z^0$ (91–94)	865 ± 31	672 ± 29	[17]
DELPHI	$1.7 \times 10^6 Z^0$ (91–93)	309 ± 22	377 ± 28	[18]
OPAL	$1.7 \times 10^6 Z^0$ (91–93)	697 ± 37	292 ± 23	[19]
CDF	20 pb^{-1} Run 1a	889 ± 35	558 ± 35	[20]

DELPHI and SLD report measurements of $\tau(\bar{B}^0)$ and $\tau(B^-)$ based on inclusive vertexing with charge determination. In the DELPHI analysis, B hadrons are selected as jets with a secondary vertex[b] and the sum of the charges of the tracks associated to the secondary vertex determines the B hadron charge. A minimum of three tracks must be associated with the secondary vertex, and no attempt is made to distinguish between the B vertex and the subsequent charmed particle vertex. This procedure finds 1817 B candidates in a sample of 1.4×10^6 hadronic Z^0 decays. According to Monte Carlo simulation, these events are $99.1 \pm 0.3\%$ pure in the reaction $Z^0 \to b\bar{b}$, and 83% (70%) of the B hadrons measured as neutral (charged) are indeed from neutral (charged) B hadrons. The mean lifetime of the mixture of neutral B hadrons in this data sample is $1.58 \pm 0.11 \pm 0.09$ psec (the first error is statistical and the second error is systematic). Correcting for the contribution to the sample from $\bar{B}_s^0$ and Λ_b^0, they find a $\bar{B}^0$ lifetime of $\tau(\bar{B}^0) = 1.63 \pm 0.14 \pm 0.13$ psec. The B^- lifetime is $\tau(B^-) = 1.72 \pm 0.08 \pm 0.06$ psec.

SLD uses two methods to determine $\tau(\bar{B}^0)$ and $\tau(B^-)$ from a sample of 1.5×10^5 hadronic Z^0 decays. In the first method, they select a sample of high p and p_t^{rel} leptons that come from B hadron semileptonic decay. Next they try to reconstruct the associated charmed particle from tracks that are inconsistent with coming from the interaction point. The method is similar to the method based on the $\ell + D$ signature, except they do not reconstruct the D meson exclusively. The tracks associated with the charmed particle decay are combined to form a vertex, and the charmed particle is intersected with the lepton to form the B decay point. The B hadron charge is

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[b]The term "secondary vertex" implies that the charged particle trajectories of the particles in the jet are consistent with originating from a position (the B hadron decay point) other than the collision point (the B hadron production point). The vertex may be reconstructed in a plane or in space. The reconstructed collision point or interaction point is often referred to as the "primary vertex."

determined from the tracks associated to the B decay point. This method isolates 977 semileptonic B decays, of which 428 are reconstructed as neutral and 549 are reconstructed as charged. The predicted fractions of $\bar{B}^0$ and B^- in these two samples are 65.4% and 70.1%, respectively.

The second method employed by SLD is similar to the topological method of DELPHI, described above. Using track impact parameters they isolate a subsample of 14 000 hadronic decays that is 90% pure in the process $Z^0 \rightarrow b\bar{b}$. Next they associate tracks with a single secondary vertex in each event hemisphere. As in the DELPHI analysis, the tracks associated to this vertex come from B hadron decay and the decay of the associated charmed particle. Exploiting the unique vertexing capabilities of SLD, a novel algorithm is used to reconstruct vertices in three-dimensions; 8685 vertices are reconstructed, with a predicted B purity of exceeding 99%. These vertices are classified into 3382 neutral B decays and 5303 charged B decays, which are 55.5% $\bar{B}^0$ and 56.2% B^-, respectively. This sample of inclusively reconstructed neutral and charged B decays is significantly larger than the sample reconstructed with DELPHI (albeit with poorer separation between charged and neutral B hadrons) despite starting with an order of magnitude less statistics. The resulting lifetimes are reported in Table 4 ($\bar{B}^0$) and Table 5 (B^-).

Table 4. Summary of $\bar{B}^0$ lifetimes. The first error is the statistical error, and the second error is the systematic error.

Experiment	Method	Data Set	Result (psec)	Reference
ALEPH	$\ell + D$	91–94	$1.61 \pm 0.07 \pm 0.04$	17
ALEPH	exclusives	91–94	$1.25^{+0.15}_{-0.13} \pm 0.05$	17
ALEPH	$\pi^+\pi^-$	91–94	$1.49^{+0.17+0.08}_{-0.15-0.06}$	17
DELPHI	$\ell + D$	91–93	$1.61^{+0.14}_{-0.13} \pm 0.08$	18
DELPHI	vertex charge	91–93	$1.63 \pm 0.14 \pm 0.13$	21
OPAL	$\ell + D$	91–93	$1.53 \pm 0.12 \pm 0.08$	19
LEP Average			1.55 ± 0.06	22
SLD	$\ell +$ vertex	93–95	$1.60^{+0.15}_{-0.14} \pm 0.10$	23
SLD	vertex charge	93–95	$1.55 \pm 0.07 \pm 0.12$	23
CDF	$\ell + D$	Run 1a	$1.57 \pm 0.08 \pm 0.07$	20
CDF	excl. $(J/\psi K)$	Run 1a/1b	$1.64 \pm 0.11 \pm 0.06$	24
World Average			1.56 ± 0.05	

The LEP averages reported in Table 4 and Table 5 have been determined following the methods adopted by the LEP B lifetime working group[22]. In forming these averages, an attempt is made to standardize assumptions about aspects of the measurements that are common to a particular method of measuring a lifetime (for example, the value of f^{**} in the lepton plus charm measurements). The world averages in these Tables adopt the same assumptions used in forming the LEP averages. If instead the individual results are combined by (1) first adding the statistical and

Table 5. Summary of B^- lifetimes. The first error is the statistical error, and the second error is the systematic error.

Experiment	Method	Data Set	Result (psec)	Reference
ALEPH	$\ell + D$	91–94	$1.58 \pm 0.09 \pm 0.04$	17
ALEPH	exclusives	91–94	$1.58^{+0.21}_{-0.18} \pm 0.04$	17
DELPHI	$\ell + D$	91–93	$1.61 \pm 0.16 \pm 0.12$	18
DELPHI	vertex charge	91–93	$1.72 \pm 0.08 \pm 0.06$	21
OPAL	$\ell + D$	91–93	$1.52 \pm 0.14 \pm 0.09$	19
LEP Average			1.62 ± 0.06	22
SLD	ℓ + vertex	93–95	$1.49^{+0.11}_{-0.10} \pm 0.05$	23
SLD	vertex charge	93–95	$1.67 \pm 0.06 \pm 0.09$	23
CDF	$\ell + D$	Run 1a	$1.51 \pm 0.12 \pm 0.08$	20
CDF	excl. $(J/\psi K)$	Run 1a/1b	$1.68 \pm 0.09 \pm 0.06$	24
World Average			1.62 ± 0.05	

systematic errors of each individual result in quadrature to get a total error (if the error is asymmetric, then symmetrize the error by choosing the larger of the two asymmetric values), and then (2) averaging these individual results weighing each result by its fractional error (σ_τ/τ), the resulting averages are very similar to the averages reported in the Tables, and the errors on the averages are only slightly smaller (by 10% at most). This agreement is not surprising since the precision of the individual measurements is dominated by statistical and uncorrelated systematic errors.

Table 6 summarizes the results on the ratio of lifetimes $\tau(B^-)/\tau(\bar{B}^0)$. The world average $\tau(B^-)/\tau(\bar{B}^0) = 1.02 \pm 0.04$ is consistent with theoretical expectations. Many systematic errors that are present in the individual lifetimes are correlated in this ratio. Due to these correlations, the average lifetime ratio determined from several experiments must be based on the average of the ratios determined by each experiment and not on the ratio of the world averages of $\tau(B^-)$ and $\tau(\bar{B}^0)$.

2.3. $\bar{B}^0_s$

There are two new results on $m(\bar{B}^0_s)$ since the last Lepton-Photon Symposium. OPAL reports[27] a new $\bar{B}^0_s \rightarrow J/\psi\phi$ candidate, which combined with their previous candidate yields a mass of $m(\bar{B}^0_s) = 5367 \pm 15 \pm 5$ MeV/c^2. The first error is the statistical error, and the second error is the systematic error. CDF has submitted[28] the final analysis of the data collected during Run 1a of the Tevatron Collider (20 pb^{-1}). Based on a signal of 32 ± 6 $\bar{B}^0_s \rightarrow J/\psi\phi$ candidates, they measure $m(\bar{B}^0_s) = 5369.9 \pm 2.3 \pm 1.3$ MeV/c^2, which is an improvement of the current value reported in the Review of Particle Properties[29]: $m(\bar{B}^0_s) = 5375 \pm 6$ MeV/c^2. A similar analysis of $J/\psi K^-$ and $J/\psi K^{*0}$ candidates yields $m(\bar{B}^0) = 5281.3 \pm 2.2 \pm 1.4$ MeV/c^2, $m(B^-) = 5279.1 \pm 1.7 \pm 1.4$ MeV/c^2, respectively, yielding a mass difference of $\Delta m(\bar{B}^0_s - B) = 89.7 \pm 2.7 \pm 1.2$

Table 6. Summary of the B^0/B^+ lifetime ratio. The first error is the statistical error, and the second error is the systematic error.

Experiment	Method	Data Set	Result (psec)	Reference
ALEPH	$\ell + D$	91–94	$0.98 \pm 0.08 \pm 0.02$	17
ALEPH	exclusives	91–94	$1.27^{+0.23}_{-0.19} \pm 0.03$	17
DELPHI	$\ell + D$	91–93	$1.00^{+0.17}_{-0.15} \pm 0.10$	18
DELPHI	vertex charge	91–93	$1.06^{+0.13}_{-0.11} \pm 0.10$	21
OPAL	$\ell + D$	91–93	$0.99 \pm 0.14^{+0.05}_{-0.04}$	19
LEP Average			1.04 ± 0.06	22
SLD	ℓ + vertex	93–95	$0.94^{+0.14}_{-0.12} \pm 0.07$	23
SLD	vertex charge	93–95	$1.08^{+0.09}_{-0.08} \pm 0.10$	23
CDF	$\ell + D$	Run 1a	$0.96 \pm 0.10 \pm 0.05$	20
CDF	excl. $(J/\psi K)$	Run 1a/1b	$1.02 \pm 0.09 \pm 0.01$	24
World Average			1.02 ± 0.04	

MeV/c^2, where "B" refers to the average of $\bar{B}^0$ and B^-.

The most common signature used to measure the $\bar{B}^0_s$ lifetime is opposite-charge $\ell^- D^+_s$ combinations arising from $\bar{B}^0_s \to D^+_s \ell^- \bar{\nu} X$. The most common decay modes used to reconstruct the D^+_s are $\phi\pi^+$ and $\bar{K}^{*0} K^+$. The ALEPH experiment uses the additional hadronic modes $\phi\pi\pi\pi$, $\bar{K}^0_s K^+$, and $\bar{K}^0_s K^{*+}$, as well as the semileptonic mode $\phi\ell^+\nu$. Table 7 summarizes the $\ell^- D^+_s$ signals used in the lifetime measurements. The two physics backgrounds to this $\bar{B}^0_s$ signature are

1. B meson decays in which the virtual W emitted by the b quark forms a D^-_s, yielding $B \to D^-_s D$, followed by $D \to \ell^+ \nu X$ yielding a final state with $D^-_s \ell^+$. This background is suppressed by kinematic requirements on the lepton, which has a softer p and p^{rel}_t spectrum than leptons coming from direct B semileptonic decay.

2. Semileptonic decays of B mesons $B \to \ell^- \bar{\nu} D^+_s K$, in which the c quark combines with the $\bar{s}$ quark of an $s\bar{s}$ quark-pair from the vacuum, and the spectator antiquark combines with the s quark to form a K. This decay has never been established[30] and is expected to contribute a very small background. The possible presence of this background usually contributes only to the systematic error (the lifetime is not adjusted).

There are potential reflections from B meson semileptonic decays that produce a D^+ decay via $D^+ \to \bar{K}^{*0}\pi^+$. This background can be reduced by using particle identification to reduce the fraction of pions misidentified as kaons. Finally, the largest background is combinatoric. This background can be studied by using the D^+_s sidebands and same-sign $\ell^\pm D^\pm_s$ combinations.

Four other signatures have been used to measure the $\bar{B}^0_s$ lifetime. ALEPH and DELPHI use a D^+_s vertexed with a negatively charged hadron. This signature is

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Table 7. Summary of $\ell^{\mp} D_s^{\pm}$ signal statistics (combinatorial background subtracted) for the $\bar{B}_s^0$ lifetime measurements. The number of Z^0's means hadronic Z^0 decays.

Experiment	Data Sample	Signal	Ref.
ALEPH	$3.0 \times 10^6 Z^0$ (91–94)	147 ± 14	[31]
DELPHI	$3.2 \times 10^6 Z^0$ (91–94)	85 ± 13	[32]
OPAL	$3.6 \times 10^6 Z^0$ (91–94)	84 ± 13	[33]
CDF	20 pb^{-1} Run 1a	76 ± 8	[34]

based on hadronic decays such as $\bar{B}_s^0 \to D_s^+ \pi^-$ or $D_s^+ \rho^-$, which presumably have larger branching fractions than the semileptonic mode used above. The purity (20–30%), however, of this signature is much less than in the semileptonic mode. DELPHI uses $\ell\phi$ correlations from $\bar{B}_s^0 \to D_s^+ \ell^- \bar{\nu} X$, $D_s^+ \to \phi X$, which has an estimated purity of $50 \pm 15\%$, and inclusive D_s^+, which has an estimated purity of $55 \pm 15\%$, and significant backgrounds from $B \to D_s D X$, and $Z^0 \to c\bar{c}$, $c \to D_s^+$. Finally, CDF reports a low statistics measurement based on an exclusive sample from $\bar{B}_s^0 \to J/\psi \phi$.

A summary of the different $\bar{B}_s^0$ lifetime measurements is provided in Table 8.

Table 8. Summary of $\bar{B}_s^0$ lifetimes. The first error is the statistical error, and the second error is the systematic error.

Experiment	Method	Data Set	Result (psec)	Reference
ALEPH	$\ell + D_s$	91–94	$1.59^{+0.17}_{-0.15} \pm 0.03$	[31]
ALEPH	$D_s +$ hadron	91–93	$1.61^{+0.30+0.18}_{-0.29-0.16}$	[35]
DELPHI	$\ell + D_s$	91–94	$1.54^{+0.31}_{-0.27} \pm 0.06$	[32]
DELPHI	D_s^+ hadron	92–94	$1.57^{+0.45+0.15}_{-0.37-0.14}$	[32]
DELPHI	$\ell + \phi$	93–94	$1.45^{+0.20+0.32}_{-0.23-0.16}$	[32]
DELPHI	inclusive D_s+	92–94	$1.61^{+0.34+0.18}_{-0.29-0.13}$	[32]
OPAL	$\ell + D_s$	90–94	$1.54^{+0.25}_{-0.21} \pm 0.06$	[33]
LEP Average			1.57 ± 0.11	[36]
CDF	$\ell + D_s$	Run 1a	$1.42^{+0.27}_{-0.23} \pm 0.11$	[34]
CDF	excl. ($J/\psi\phi$)	Run 1a	$1.74^{+1.08}_{-0.69} \pm 0.07$	[34]
World Average			$1.55^{+0.11}_{-0.10}$	

2.4. b-baryons

Two experiments have reported new measurements of the mass of the Λ_b. Based on an analysis of 3.3×10^6 hadronic Z^0 decays (1991–1994 data), ALEPH[37] has isolated four $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ candidates (a 2.5σ signal), which give $m(\Lambda_b^0) = 5621 \pm 17 \pm 15$ MeV/c^2, where the first error is statistical, and the second error is systematic. DELPHI reports[38] $m(\Lambda_b^0) = 5656 \pm 22 \pm 6$ MeV/c^2 based on three $\Lambda_c^+ \pi^-$ candidates from an analysis of 3×10^6 hadronic Z^0 decays (1991–1994 data). Combining these new

measurements[c] with the current world average[29] yields $m(\Lambda_b^0) = 5639 \pm 15$ MeV/c^2. One potential problem with the $\Lambda_c^+ \pi^-$ signature is that it is difficult to distinguish this final state from final states such as $\Lambda_c^+ \rho^-$, followed by $\rho^- \to \pi^- \pi^0$, and the π^0 is not observed. This incomplete reconstruction could cause a systematic underestimation of $m(\Lambda_b^0)$. Since the time of this conference, CDF has reported[39] a preliminary measurement $m(\Lambda_b^0) = 5623 \pm 5 \pm 4$ MeV/c^2 based on the observation of 38 candidates of the decay $\Lambda_b^0 \to J/\psi\Lambda$ from 115 pb^{-1} (Run 1a and 1b). The background estimate is 18; the signal significance is 3σ. The measured mass is carefully calibrated against known signals such as $\bar{B}^0 \to J/\psi K_s^0$, yielding the result $m(\Lambda_b^0) - m(\bar{B}^0) = 342 \pm 6$ MeV/c^2.

Searches for the Λ_b^0 were reported as well. Using the same data sample listed above, DELPHI has searched for the decay $\Lambda_b^0 \to J/\psi\Lambda$ and reports[38] a limit $f(b \to \Lambda_b^0) \cdot B(\Lambda_b^0 \to J/\psi\Lambda) < 7 \times 10^{-4}$ at 90% C.L., where $f(b \to \Lambda_b^0)$ is the fraction of b quarks that fragment into a Λ_b^0. OPAL reports[40] the following limits based on 1.9×10^6 hadronic Z^0 decays (1990–1993 data): $f(b \to \Lambda_b^0) \cdot B(\Lambda_b^0 \to J/\psi\Lambda) < 3.4 \times 10^{-4}$ at 90% C.L. and $f(b \to \Lambda_b^0) \cdot B(\Lambda_b^0 \to \Lambda_c^+ \pi^-) < 2.0 \times 10^{-3}$ at 90% C.L.

Two principal signatures have been used to measure $\tau(\Lambda_b^0)$, both of which are based on the semileptonic decay $\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu} X$. The first signature is opposite-sign $\ell^\pm \Lambda_c^\mp$ pairs, where the Λ_c^+ is fully reconstructed (e.g. using final states like $Kp\pi$ and $\Lambda\pi\pi$). This signature is probably the most unambiguous for the Λ_b^0, barring exclusive reconstruction, but yields fairly low statistics. Conceptually it is very similar to the other $\ell + D$ analyses above: e.g. like-sign pairs $\ell^\pm \Lambda_c^\pm$ and the Λ_c^+ sideband can be used to study the backgrounds, and kinematic cuts on the lepton can be used to suppress backgrounds. In the second signature, the Λ_c^+ is not fully reconstructed, instead the inclusive decay $\Lambda_c^+ \to \Lambda X$ is used. The signal is $\ell^- \Lambda$ pairs (and not $\ell^- \bar{\Lambda}$). This signature was used by the LEP experiments to establish the existence of b baryons. The main background is leptons from semileptonic B meson decay accompanied by Λ baryons produced in the fragmentation of the B. The sample has much higher statistics than the $\ell^\pm \Lambda_c^\mp$ sample, but suffers from two problems:

1. b baryons other than the Λ_b can contribute: $\Xi_b \to \Xi_c \ell^- \bar{\nu}$, $\Xi_c \to \Lambda X$ yields $\ell^- \Lambda$ pairs.

2. Determining the Λ_b^0 decay point is difficult, since the Λ is very long lived and must be extrapolated a long distance back to the lepton. Alternatively, the impact parameter of the lepton can be used to measure the lifetime.

The lifetime determined from the impact parameter distribution has a larger systematic uncertainty than the lifetime determined using the decay length. On the Z^0 resonance, b quarks are produced with -94% polarization. The weakly decaying B mesons are spin-0 and are unpolarized. The Λ_b, however, is spin-$\frac{1}{2}$ and may be polarized. Using a sample of $\ell^- (\Lambda\pi^+)$ pairs, ALEPH measures[41] the Λ_b polarization

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[c]DELPHI has a candidate for $\Lambda_b^0 \to D^0 p\pi^-$, which has not been included in the average.

from the distribution of $\langle E_\ell \rangle / \langle E_\nu \rangle$[42], where $\langle E_\ell \rangle$ is the mean energy of the leptons in the sample and $\langle E_\nu \rangle$ is the mean energy of the neutrino. The measured polarization is $P(\Lambda_b^0) = -0.23^{+0.24+0.08}_{-0.20-0.07}$; the initial b quark polarization can be diminished due to gluon radiation and cascade decays such as $\Sigma_b \to \Lambda_b \pi$.

OPAL measures the lifetime in the $\ell^- \Lambda$ sample using both the decay length and the lepton impact parameter. The lifetime measured with the lepton impact parameter is corrected by $+0.065 \pm 0.065$ psec to account for possible b baryon polarization, the corresponding correction using the decay length is $+0.03 \pm 0.03$ psec, a factor two less.

A summary of lifetime measurements based on the $\ell^- \Lambda_c^+$ and $\ell^- \Lambda$ signatures is presented in Table 9.

Three of the LEP experiments report searches for the strange b baryon Ξ_b, which is either Ξ_b^- (bsd) or Ξ_b^0 (bsu). The signature is $\ell^\pm \Xi_s^\pm$ pairs from the decay sequence $\Xi_b \to \ell^- \bar{\nu} \Xi_c X$, $\Xi_c \to \Xi_s^- X$, $\Xi_s^- \to \Lambda \pi^-$. The physics backgrounds are (1) $\Lambda_b^0 \to \ell^- \bar{\nu} \Lambda_c^+ X$, $\Lambda_c^+ \to \Xi^- K^+ \pi^+$, and (2) B meson decays such as $B \to \Xi_c \Lambda_c^- X$, $\Xi_c \to \Xi^- X$ and $\Lambda_c^- \to \ell^- X$. Both these backgrounds are expected to be small, but four body semileptonic decays of the Λ_b could also contribute to the signature and have not been estimated.

ALEPH, DELPHI, and OPAL all report excesses of same-sign $\ell^\pm \Xi_s^\pm$ pairs over opposite-sign pairs. ALEPH and DELPHI use this excess to calculate a signal and determine a lifetime. OPAL reports a limit on the production of Ξ_b, since there are sources of $\ell^\pm \Xi_s^\pm$ pairs of unknown magnitude from Λ_b decay. The results are summarized in Table 10.

Table 9. Summary of b baryon lifetimes. The first error is the statistical error, and the second error is the systematic error.

Experiment	Method	Data Set	Result (psec)	Reference
ALEPH	$\ell + \Lambda_c$	91–94	$1.24^{+0.15}_{-0.14} \pm 0.05$	43
DELPHI	$\ell + \Lambda_c$	91–94	$1.26^{+0.26+0.03}_{-0.22-0.05}$	44
OPAL	$\ell + \Lambda_c$	90–94	$1.14^{+0.22}_{-0.19} \pm 0.07$	45
ALEPH	$\ell + \Lambda$	91–94	$1.21 \pm 0.09 \pm 0.07$	43
DELPHI	$\ell + \Lambda$	91–94	$1.10^{+0.16+0.05}_{-0.14-0.08}$	44
DELPHI	$\mu + p$	92	$1.27^{+0.35}_{-0.29} \pm 0.09$	46
OPAL	$\ell + \Lambda$	90–94	$1.16 \pm 0.11 \pm 0.06$	47
LEP Average			1.18 ± 0.07	22
ALEPH	$\ell + \Xi$	91–94	$1.25^{+0.55}_{-0.35} \pm 0.20$	48
DELPHI	$\ell + \Xi$	91–93	$1.50^{+0.7}_{-0.4} \pm 0.30$	49
Average $\ell + \Xi$			$1.36^{+0.44}_{-0.33}$	22

Table 10. Summary of results on the strange b baryon Ξ_b. When two errors are listed, the first error is the statistical error, and the second error is the systematic error. The DELPHI lifetime result is based on a subset of the data sample: $1.7 \times 10^6 Z^0$ (91–93), which has 10 candidates (7 same-sign and 3 opposite-sign).

Experiment	ALEPH	DELPHI	OPAL
# hadronic Z^0	3.45×10^6 (90–94)	3.06×10^6 (91–94)	3.61×10^6 (90–94)
Excess of $\ell^\pm \Xi_s^\pm$ over $\ell^\pm \Xi_s^\mp$	22.5 ± 5.7	14.0 ± 3.7	29 ± 14
$f(b \to \Xi_b) \times$ $B(\Xi_b \to \Xi \ell \nu X)$	$(5.3 \pm 1.3 \pm 0.7)$ $\times 10^{-4}$	$(6.6 \pm 1.7 \pm 1.0)$ $\times 10^{-4}$	$< 5.1 \times 10^{-4}$ at 95% C.L.
τ (psec)	$1.25^{+0.55}_{-0.35} \pm 0.20$	$1.50^{+0.7}_{-0.4} \pm 0.30$	$-$
Reference	48	44	50

2.5. Search for B_c

The B_c^- meson is a bound state of a b quark and a $\bar{c}$ quark ($b\bar{c}$) that decays weakly and therefore is very narrow. Reliable calculations of the mass and decay of this bound state exist. There are 15 expected states below BD threshold. Some of the predicted properties[51] are $m(B_c^-) = 6256 \pm 20$ MeV/c^2, $\tau(B_c^-) = 1.35 \pm 0.15$ psec[d] $B(B_c^- \to J/\psi X) \sim 10\%$. At the Tevatron, the production rate is expected to be $\sim 10^{-3}$ of the production rate of the lighter B hadrons; at the Z^0 resonance, a few hundred B_c^- are expected for every 10^6 hadronic Z^0 decays.

Related to the search for the B_c^- is the observation[52] of Υ production at the Z^0 by OPAL. Starting with a sample of 3.7×10^6 hadronic Z^0 decays, they find 8 candidates for the process $Z^0 \to \Upsilon X$, $\Upsilon \to \mu^+ \mu^-$ or $\Upsilon \to e^+ e^-$, where Υ means either $\Upsilon(1S)$, $\Upsilon(2S)$, or $\Upsilon(3S)$, which OPAL can not distinguish experimentally. The estimated background is 1.6 ± 0.3. The measured branching fraction is $B(Z^0 \to \Upsilon X) = (1.0 \pm 0.4 \pm 0.1 \pm 0.2) \times 10^{-4}$, where the first error is statistical, the second is the experimental systematic error, and the third error is the systematic error due to uncertainties in the production mechanism. The observed rate is an order of magnitude larger than the rate expected from so-called colour-singlet models[52], which are dominated by the production of Υ's via b quark fragmentation: $Z^0 \to b\bar{b}, b \to \Upsilon$. This same process should lead to B_c^- formation. The discrepancy between the expected and observed rate could originate from (1) a statistical fluctuation, (2) additional production mechanisms such as those predicted by so-called colour-octet models[52], or (3) an underestimate of the production via b quark fragmentation, which could indicate that the B_c^- production may be underestimated as well.

The B_c^- has a clean signature, based on the spectator decay in which the b quark

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[d]Some lifetime calculations predict significantly shorter lifetimes.

decays to a c quark and a virtual W^*; the c and spectator $\bar{c}$ form a J/ψ and the W^* becomes $\ell^-\bar{\nu}$ or a π^-. The predicted branching fractions (including the J/ψ branching fractions) are $B(B_c^- \to J/\psi\pi^-) \cdot B(J/\psi \to \ell^+\ell^-) \sim 3 \times 10^{-4}$, and $B(B_c^- \to J/\psi\ell^-\bar{\nu}) \cdot B(J/\psi \to \ell^+\ell^-) \sim 10^{-3}$.

Two experiments have reported[e] searches. Starting with a sample of 600 J/ψ candidates from 3.1×10^6 hadronic Z^0 decays (1991–1994), ALEPH finds[53] no candidates in the final state $J/\psi\pi$, one candidate in the final state $J/\psi\mu\nu$, and one candidate in the final state $J/\psi e\nu$. The expected backgrounds are 0.32, 0.17, and 0.13, respectively. The probability for the observed two events to come from the expected background is 4%, and they report the following limits at 90% C.L.:

$$\frac{B(Z \to B_c X)}{B(Z \to q\bar{q})} \cdot B(B_c^- \to J/\psi\pi^-) < 4 \times 10^{-5},$$

$$\frac{B(Z \to B_c X)}{B(Z \to q\bar{q})} \cdot B(B_c^- \to J/\psi\ell^-\bar{\nu}) < 7 \times 10^{-5}.$$

CDF searches[54] for a peak in the invariant mass distribution of $J/\psi\pi^-$ candidates between 6.1 GeV/c^2 and 6.4 GeV/c^2. No signal is observed, and they set a limit on the product of the production cross-section times the branching fraction, $\sigma(p\bar{p} \to B_c^- X) \cdot B(B_c^- \to J/\psi\pi^-)$, normalized to their observed $B^+ \to J/\psi K^-$ signal. The limit is 0.12 for $\tau(B_c^-) = 0.17$ psec and decreases to 0.068 for $\tau(B_c^-) = 1.6$ psec.

3. Results on B^* and B^{**}

In Heavy Quark Effective Theory (HQET), the heavy and light quarks decouple as the heavy quark mass increases. The spin-angular momentum of the heavy quark, $\vec{s}_Q$ and the total angular momentum of the light quark, $\vec{j}_q = \vec{l} + \vec{s}_q$, are conserved separately. A $Q\bar{q}$ bound state has total angular momentum $\vec{J} = \vec{s}_Q \oplus \vec{j}_q$, so for each value of j_q there is a doublet. In the case of B mesons, the doublet of particles that corresponds to the case in which the light quark has zero angular momentum ($l = 0$) is the familiar B ($J^P = 0^-$) and B^* ($J^P = 1^-$) mesons. For $l = 1$, there are two values of j_q ($\frac{1}{2}$ and $\frac{3}{2}$), and two corresponding doublets. These four p-wave mesons are collectively referred to as the B^{**}'s. Their expected properties[55] are summarized in Table 11.

Observation of a new state is always interesting in itself, and the observed properties of the B^{**}'s provide a test of predictions of HQET. The real motivation for searching for B^{**}'s, however, is that they may provide an effective b flavour tag for CP-violation experiments. For example, a B_2^{*-} ($b\bar{u}$) can decay to a $\bar{B}^0\pi^-$; the negative charge of the pion signals the flavour of the $\bar{B}^0$ at production. Actually the idea of exploiting the pions from the B^{**} resonances as a flavour tag was preceeded by the

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[e]Following the symposium, OPAL has submitted a search[27] for the B_c^- for publication.

Table 11. The expected p-wave B meson ($b\bar{d}$ and $b\bar{u}$) states and their predicted[55] masses, widths, and decay modes. In the final column (Decay Modes), the L refers to the orbital angular momentum of the $B\pi$ system. Angular momentum conservation and parity require $L = 0$ or $L = 2$. For the predicted B^{**} masses, $B\rho$ decays are suppressed by phase-space.

State	$J^P(j_q)$	Mass (MeV/c^2)	Width (MeV/c^2)	Decay Modes
B_2^*	$2^+(\frac{3}{2})$	5771	25	$(B^*\pi)_{L=2}, (B\pi)_{L=2}$
B_1	$1^+(\frac{3}{2})$	5759	21	$(B^*\pi)_{L=2}$
B_1	$1^+(\frac{1}{2})$	~ 5670	broad	$(B^*\pi)_{L=0}$
B_0^*	$0^+(\frac{1}{2})$	~ 5670	broad	$(B\pi)_{L=0}$

idea[56] of using associated fragmentation particles as a flavour tag. For example, if a b quark is produced, and a $d\bar{d}$ pair materializes out of the vacuum, then the b and the $\bar{d}$ may form a $\bar{B}^0$ meson, and the left over d quark could combine with a $\bar{u}$ quark to form a π^-. As in the above example, the charge of the pion signals that a $\bar{B}^0$ was produced. The narrow B^{**} resonances, however, potentially provide much better signal-to-noise and, therefore, a cleaner flavour tag. Results on flavour tagging from ALEPH and OPAL using these methods are presented later in this section.

Results on excited B_s states and b baryon states were also submitted to this conference. The expected properties of these particles are summarized in Tables 12 and 13. A significant production of B_s^{**} actually reduces the production of weakly decaying B_s^0. Furthermore, since $B_s^{**} \to B^0\bar{K}^0$, and the $\bar{K}^0$ is neutral, B_s^{**} production does not provide a flavour tag for B^0. A significant production of $\Sigma_b^{(*)}$ reduces the polarization of weakly decaying Λ_b^0.

Table 12. The expected p-wave B_s meson ($b\bar{s}$) states and their predicted[55] masses, widths, and decay modes. In the final column (Decay Modes), "B" means $b\bar{u}$ or $b\bar{d}$. The widths of the $j_q = \frac{1}{2}$ doublet are hard to predict since the BK decays may be phase-space suppressed. $B_s\pi$ decays are forbidden by isospin.

State	$J^P(j_q)$	Mass (MeV/c^2)	Width (MeV/c^2)	Decay Modes
B_{s2}^*	$2^+(\frac{3}{2})$	5849	1	$(B^*K)_{L=2}, (BK)_{L=2}$
B_{s1}	$1^+(\frac{3}{2})$	5861	4	$(B^*K)_{L=2}$
B_{s1}	$1^+(\frac{1}{2})$	~ 5750	?	$(B^*K)_{L=0}$ or $B_s\gamma$
B_{s0}^*	$0^+(\frac{1}{2})$	~ 5750	?	$(BK)_{L=0}$ or $B_s\gamma$

Table 13. The reported excited b baryons and their expected properties[57]. The total spin angular momentum of the two light quarks is denoted by s_{qq}, and $\vec{J} = \vec{s}_b \oplus \vec{s}_{qq}$.

State	$J^P(s_{qq})$	$M(\Sigma_b) - M(\Lambda_b)$ (MeV/c^2)	Decay Modes
Λ_b^0	$\frac{1}{2}^+(0)$	$-$	weak
Σ_b	$\frac{1}{2}^+(1)$	200 ± 20	$\Lambda_b^0\pi$
Σ_b^*	$\frac{3}{2}^+(1)$	230 ± 20	$\Lambda_b^0\pi$

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Results on B^* and B^{**} were reported by the LEP collaborations. There are two approaches (1) *inclusive B reconstruction* (results from ALEPH, DELPHI, L3, and OPAL), which yields large samples ($\sim 10^5$) of B's; and (2) *exclusive B reconstruction* (results from ALEPH), which is cleaner, but has much lower statistics (~ 500 B's).

3.1. Inclusive B Hadron Reconstruction

Inclusive B hadron reconstruction is possible because of the long B hadron life-time, the large B hadron mass, and the hard b quark fragmentation. There have been three approaches. The first published method[58] of inclusive B hadron reconstruction was from the L3 collaboration. Their approach was used to reconstruct the B^* and is discussed in more detail in that section. The second method[59] was developed by OPAL. It distinguishes between charged B's and neutral B's, and as we shall see, this charge assignment makes it possible to determine background rates and flavour tagging efficiencies from the data. A third method[60] was developed by DELPHI, and is also used by ALEPH[61]. This method has higher efficiency than the OPAL method, but does not determine the B hadron charge. Monte Carlo models are used to determine the background.

The method of DELPHI and ALEPH proceeds as follows. First $Z^0 \rightarrow b\bar{b}$ events are selected using track impact parameters. A purity of 80–90% is achieved with good efficiency. Next charged tracks and neutral calorimeter clusters are combined based on their rapidity y and impact parameter δ. The rapidity is defined with respect to the thrust axis of the event or a jet axis. Charged tracks are assigned the pion mass, and neutral clusters are treated as photons. The large B mass and hard B fragmentation gives the decay products from B hadrons a harder rapidity distribution than fragmentation products and particles not coming from B decay. The long B hadron lifetime gives the charged particles from B hadron decay larger impact parameters (with respect to the interaction point) on average. To reduce the fraction of poorly measured B's, requirements are made on the reconstructed B mass, and the reconstructed energy or momentum. The raw B energy is corrected to account for undetected neutrinos, detector inefficiencies, and incorrect particle mass assignments. This correction depends on the reconstructed B mass and the observed energy in the hemisphere.

The OPAL approach is to select hadronic Z^0 decays and then find the jets in these events using a cone algorithm. Next they search for secondary vertices in the two highest energy jets. If a vertex is found, they assign a vertex charge Q_{vtx}, which is defined as follows:

$$Q_{vtx} = \sum_{i=tracks} w_i q_i,$$

where w_i is a weight that is larger if the track is consistent with coming from the secondary vertex and smaller if the particle is consistent with coming from the interaction point. The Q_{vtx} distribution observed in the data is compared with the

predicted distribution from Monte Carlo simulation in Figure 3. The momentum of the vertex is also calculated using these weights, and neutral energy is added to the charged momentum to get the total B energy. The B energy resolution is improved by a factor of two by taking advantage of the known center-of-mass energy of the collision.
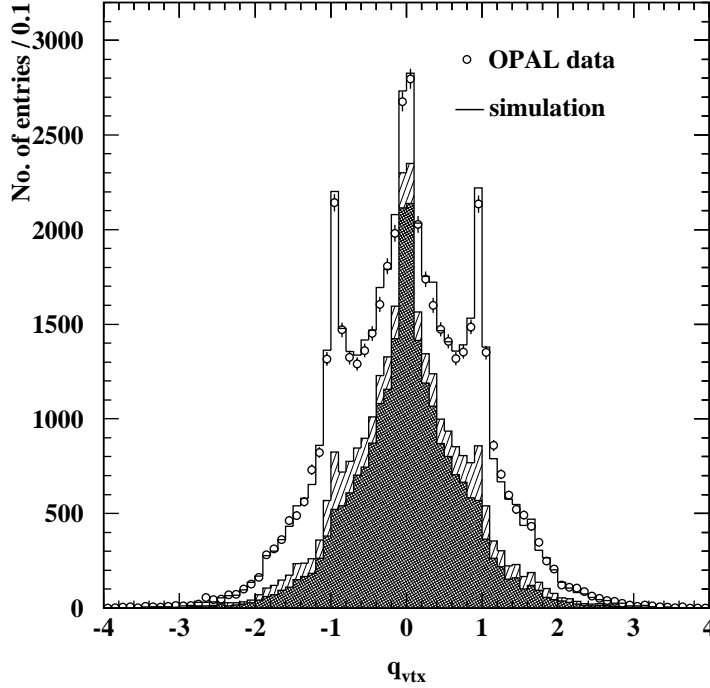

Fig. 3. The distribution of Q_{vtx} observed in the OPAL data (points) compared to the expectations from Monte Carlo simulation (histogram). The solid region represents the expected contribution from neutral B hadrons, the hatched region shows the expected contribution from sources other than B hadrons, and the remaining contribution is from $B^{\pm}$. The requirement $Q_{vtx} > 0.6$ increases the overall fraction of $B^{\pm}$ from $(40 \pm 3)\%$ to $(54 \pm 2)\%$.

The method of DELPHI and ALEPH and the method of OPAL achieve similar resolutions. The typical B hadron energy resolution is $\sigma_E/E = 7 - 9\%$, and the typical angular resolutions are $\sigma_\phi = 10 - 15$ mrad and $\sigma_\theta = 15$ mrad, where θ and ϕ are the polar and azimuthal angles, respectively. These resolutions are for the core of the distributions; there are significant non-Gaussian tails. For their B^* (B^{**}) search, ALEPH reconstructs $460\,000$ ($90\,000$) inclusive B hadrons with a purity of $94 \pm 2\%$ ($98.5 \pm 1.5\%$) in a sample of 3 million hadronic Z^0 decays. DELPHI achieves similar efficiencies. OPAL reconstructs $80\,000$ B hadrons with a purity of $89 \pm 2\%$ in 3.5

million hadronic Z^0 decays.

3.2. Results on B^*

The mass difference[29] between the B and B^* mesons is $\Delta M(B^* - B) = 46 \pm 0.6$ MeV$/c^2$, so the B^* can decay to a B only via a photon: $B^* \rightarrow B\gamma$. On the Z^0 resonance, the mean energy of this γ is 300 MeV, and the maximum energy is 800 MeV. In addition to reconstructing the B, there is the experimental challenge of measuring these relatively low energy photons. Instead of using their electromagnetic calorimeters, ALEPH and DELPHI rely on their tracking systems to reconstruct the photon when it converts. Using conversions, DELPHI (ALEPH) measures the energy of these photons down to $E_\gamma = 100(200)$ MeV. To increase statistics, they also use conversion candidates in which only one leg of the conversion is reconstructed in the tracking system. They then combine these photons with the B hadrons reconstructed inclusively as described above to form $\Delta M = M(B\gamma) - M(B)$. They see a peak at the known B^*–B mass difference.[f]

L3 measures E_γ in their high resolution BGO calorimeter; the minimum photon energy is 100 MeV. They reconstruct B hadrons starting with a sample of high p, high p_t^{rel} muons. The muon is combined with the closest jet to form the B direction. The B momentum is fixed at 37 GeV$/c$ (this approach is adequate, again, due to the hard B fragmentation). This procedure results in a B purity of 84%, a B angular resolution of 35 mrad, and an energy resolution of 20%. The B^* signal appears as an enhancement in the distribution of E_{rest}^γ, which is the energy of the photon in the rest frame of the B. Since $M(B^*) - M(B) \ll M(B)$, the recoil of the B is negligible, and E_{rest}^γ is a good approximation of the mass difference.

The results for the mass difference $\Delta M = M(B^*) - M(B)$, the relative production, and the polarization of the B^* on the Z^0 resonance from ALEPH, DELPHI, and L3 are summarized in Table 14. The measurements of the mass difference are comparable in precision to measurements made by CUSBII[62], $\Delta M = 45.6 \pm 0.8$ MeV$/c^2$, and CLEOII[63], $\Delta M = 46.2 \pm 0.3 \pm 0.8$ MeV$/c^2$ in e^+e^- collisions at $\sqrt{s} = 10.61 - 10.70$ GeV. The relative production, denoted $N_{B^*}/(N_{B^*} + N_B)$ is the number of B^* produced divided by the total number of B^* and B produced. Based on spin counting, and neglecting the small mass difference $M(B^*) - M(B)$, this ratio is expected to be 0.75. Significant production of B^{**} could alter this expectation. The equivalent ratio measured[64] for charm is 0.51 ± 0.04. ALEPH and DELPHI have measured the fraction of longitudinally polarized B^*, $\sigma_L/(\sigma_L + \sigma_T)$, using the angular distribution of the photon in the B^* rest frame. The expected value of this ratio, based on spin counting, is 0.33. The measured values of $N_{B^*}/(N_{B^*} + N_B)$ and $\sigma_L/(\sigma_L + \sigma_T)$ agree with the expectations based on spin counting.

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[f]The analyses presented here do not distinguish between B^{*0} and B_s^{*0}.

Table 14. Summary of results for the mass difference $\Delta M = M(B^*) - M(B)$, the relative production, and the polarization of the B^* on the Z^0 resonance from ALEPH, DELPHI, and L3. The L3 experiment reports the energy of the photon in the B restframe, rather than $M(B^*) - M(B)$. Since $M(B^*) - M(B) \ll M(B)$, the recoil of the B is negligible, and E_{rest}^γ is a good approximation of the mass difference. For all reported measurements, the first error is statistical and the second error is systematic.

Experiment	ALEPH	DELPHI	L3
# hadronic Z^0	3.0×10^6 (91–94)	2.3×10^6 (91–94)	1.6×10^6 (91–93)
ΔM (MeV/c^2)	$45.3 \pm 0.35 \pm 0.87$	$45.5 \pm 0.3 \pm 0.8$	46.3 ± 1.9 (stat.)
$\frac{N_{B^*}}{N_{B^*}+N_B}$ (%)	$77.1 \pm 2.6 \pm 7.0$	$72 \pm 3 \pm 6$	$76 \pm 8 \pm 6$
$\frac{\sigma_L}{\sigma_L+\sigma_T}$ (%)	$33 \pm 6 \pm 5$	$32 \pm 4 \pm 3$	–
Reference	61	60	58

3.3. Results on B^{**}

ALEPH, DELPHI, and OPAL combine their inclusively reconstructed B's with charged pions and look for resonant structure in the $B\pi$ mass distribution (or the equivalent Q distribution, where $Q = M(B\pi) - M(B)$ or $Q = M(B\pi) - M(B) - M(\pi)$). All three experiments require that candidate pions are (1) consistent with coming from the primary interaction point (this reduces combinatoric background from charged particles from B decay), and are (2) identified as pions using dE/dx measurements or RICH (DELPHI only). Using this reconstruction procedure, decays of the type $B^{**} \to B^*\pi$, $B^* \to B\gamma$ are shifted down in mass (or Q) by 46 MeV/c^2 with respect to the decays $B^{**} \to B\pi$; they do not cause significant broadening, however, of the observed resonant structure. The $B\pi$ mass distribution from OPAL is shown in Figure 4, and the Q distribution from ALEPH is shown in Figure 5. All three experiments observe resonant structure and they fit this structure with a Gaussian or Breit-Wigner. The results are summarized in Table 15. The fitted widths are broader than the experimental resolution (≈ 40 MeV/c^2) expected for a single narrow state. The experiments also fit the observed enhancement to a variety of models based on the expected contributions of the four p-wave mesons. The expected p-wave mesons qualitatively describe the data, but it is not possible to distinguish contributions from a specific state. DELPHI examined[65] the distribution of the helicity angle, α_π, defined as the angle between the momentum of the pion candidate in the $B\pi$ rest frame and the momentum of the $B\pi$ in the laboratory. Their data are consistent with a flat helicity angle distribution.

Table 15 also summarizes the production fraction, $\frac{B(Z \to b \to B_{u,d}^{**})}{B(Z \to b \to B_{u,d})}$, which is determined assuming $B^{(*)}\pi$ decays are dominant and that $B(B^{**} \to B^{(*)}\pi^\pm) = 2 \cdot B(B^{**} \to B^{(*)}\pi^0)$ (isospin). A substantial fraction of b quarks fragment into p-wave mesons.
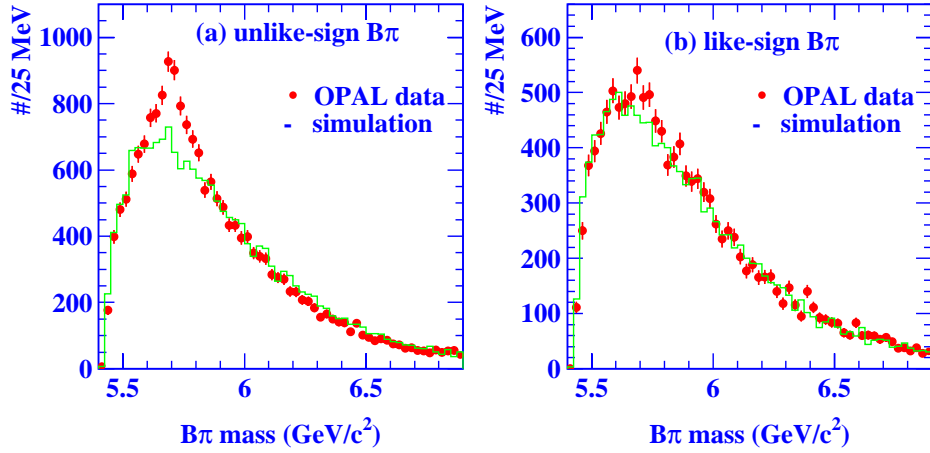
Fig. 4. The $B\pi$ mass distribution from OPAL for (a) unlike-sign $B\pi$ combinations, which are defined by $q_{vtx} \cdot q_\pi < -0.71$, and for (b) like-sign $B\pi$ combinations, which are defined by $q_{vtx} \cdot q_\pi > 0.49$. The points are the data, and the histogram is the Monte Carlo simulation, which does not contain B^{**}. The Monte Carlo is normalized to the same number of secondary vertices observed in the data. The observed enhancement in the unlike-sign data is attributed to B^{**} production.

DELPHI and OPAL have also reported evidence of B_s^{**}. The results are summarized in Table 16. In this case, the charged particle that is combined with the inclusive B is identified as a kaon using either dE/dx measurements or RICH (DELPHI only). Furthermore, DELPHI uses jet-charge flavour tagging to improve signal to background. OPAL observes one peak, and DELPHI observes two narrow peaks (see Figure 6), which they interpret as coming from the $j_q = \frac{3}{2}$ doublet, B_s^2 and B_s^1. Given the experimental resolution, the width of the peak at higher mass (presumably due to B_s^2) is 1.5σ narrower than expected.

3.4. Results on Excited b Baryons

DELPHI has reported[66] evidence for Σ_b and Σ_b^* decaying into $\Lambda_b\pi$. They enhance the fraction of Λ_b in their sample of inclusively reconstructed B hadrons by requiring that at least one of the two most energetic particles in the hemisphere of the inclusive B be (1) an identified proton (using dE/dx and RICH), (2) a Λ, or (3) a neutral cluster in the hadronic calorimeter that exceeds 10 GeV in energy. In this baryon-enriched sample, they find two enhancements in the $Q = M(\Lambda_b\pi) - M(\Lambda_b) - M(\pi)$ distribution (see Figure 7). The characteristics of these enhancements are summarized in Table 17. They reverse their baryon-enrichment requirements and find no evidence of either signal (see Figure 7); the data distribution determined with these reverse criteria are used to determine the background. They examine the helicity angle of the pion in the $\Sigma_b^{(*)}$ rest-frame and find an indication of suppression of $\pm\frac{3}{2}$ helicity states. This suppression combined with significant production rates of excited b baryons could lead to a substantial reduction of Λ_b^0 polarization[67].
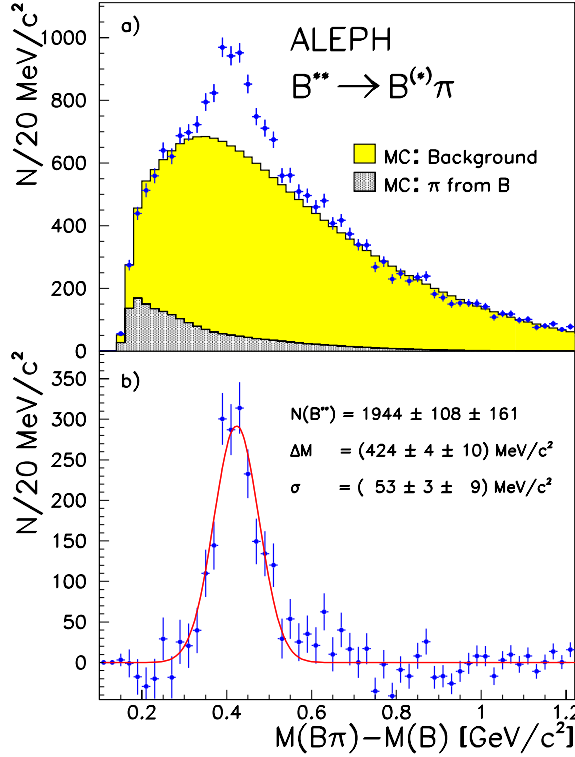
Fig. 5. (a) The $Q = M(B\pi) - M(B)$ distribution observed by ALEPH. The points are the data and the histogram is the background predicted by the Monte Carlo, normalized to fit the data in the sidebands, $Q < 0.25$ GeV/c^2 and $0.7 < Q < 1.2$ GeV/c^2. The lower histogram shows the expected background from soft pions from B decay. The modelling of these soft pions has been adjusted[61] according to data from the $\Upsilon(4S)$. (b) The difference between the data and the Monte Carlo. The observed enhancement is fit to a Gaussian, resulting in the parameters shown in the Figure and listed in Table 15.

3.5. B^{**} from Exclusively Reconstructed B Mesons

ALEPH has reported[69] the observation of a $B\pi$ resonance using exclusively reconstructed B hadrons. To reconstruct the B hadrons, they use a variety of decay modes; most of the statistics come from the final states with a D or D^* meson combined with $\pi^\pm$, a $\rho^\pm$, or an $a_1^\pm$. These same final states were used in the $\bar{B}^0$ and B^- lifetime measurements discussed previously, but the selection requirements are relaxed to increase statistics. The sample consists of 198 $\bar{B}^0$ candidates, 186 B^- candidates, and an additional 90 B^- candidates in which a γ or π^0 from D^{*0} decay has not been detected. The purity of the sample is estimated to be $(82 \pm 5)\%$.

Next they select candidate pions to combine with the B hadron. The selected track is required to be consistent with originating from the interaction point and must have a measured dE/dx consistent with a pion. The charge of the pion from B^{**} decay is correlated with b quark flavour: the combinations $B^-\pi^+$ and $\bar{B}^0\pi^-$

Table 15. Summary of results on $B^{**}_{u,d}$. All results have been converted to $Q = M(B\pi) - M(B) - M(\pi)$. The fitted parameters for Gaussians or Breit-Wigners are reported[68]. The OPAL results are for $B^-\pi^+$ combinations only. The production ratio is defined as $\frac{B(Z \to b \to B^{**}_{u,d})}{B(Z \to b \to B_{u,d})}$, and is determined assuming $B^{(*)}\pi$ decays are dominant and isospin. For all reported measurements, the first error is statistical and the second error is systematic. Note that the observed signal for DELPHI corresponds to the 91–93 data set.

Experiment	ALEPH	DELPHI	OPAL
# hadronic Z^0	3.0×10^6 (91–94)	2.3×10^6 (91–94)	3.5×10^6 (91–94)
Signal	$1944 \pm 108 \pm 161$	$2157 \pm 120 \pm 323$	$1738 \pm 121 \pm 153$
Q (MeV/c^2)	$284 \pm 4 \pm 10$	$285 \pm 5 \pm 12$	262 ± 11
σ (MeV/c^2)	$53 \pm 3 \pm 9$	$72 \pm 5 \pm 8$	60 ± 8
Γ (MeV/c^2)	–	120 ± 21	116 ± 24
Prod. ratio (%)	$27.9 \pm 1.6 \pm 5.9 \pm 3.8$	$32.5 \pm 1.9 \pm 6.0$	$27.0 \pm 1.2 \pm 5.3$
Reference	61	65	59

Table 16. Summary of results on B^{**}_s. All results have been converted to $Q = M(B\pi) - M(B) - M(K)$. The fitted parameters for a Gaussian are reported. OPAL reports results from a single Gaussian fit, and DELPHI fits their observed enhancement to two Gaussians. The production ratio is defined as $\frac{B(Z \to b \to B^{**}_s)}{B(Z \to b)}$. For all reported measurements, the first error is statistical and the second error is systematic.

Experiment	DELPHI	OPAL
Data Sample	$2.3 \times 10^6 Z^0$ (91–94)	$3.5 \times 10^6 Z^0$ (91–94)
Signal	$577 \pm 49 \pm 70$	149 ± 31
Q (MeV/c^2)	$70 \pm 4 \pm 8$ $142 \pm 4 \pm 8$	80 ± 15
σ (MeV/c^2)	$21 \pm 4 \pm 4$ $13 \pm 4 \pm 4$	36 ± 5
Prod. ratio (%)	$2.1 \pm 0.5 \pm 0.7$ $1.6 \pm 0.5 \pm 0.7$	$2.1 \pm 0.4 \pm 0.5$
Reference	65	59

(and charge conjugate) are right-sign combinations, and the combinations $B^-\pi^-$ and $\bar{B}^0\pi^+$ are wrong-sign combinations. Resonant structure should appear only in right-sign combinations; the wrong-sign combinations can be used as one measure of the background.

Background pions come mainly from fragmentation. To reduce this background, they choose the pion candidate that has the maximum component of momentum projected on the B candidate momentum. Since the b quark has a hard fragmentation function, pions from B^{**} decay satisfy this requirement more often than pions produced in the fragmentation of the b quark.

The observed resonant structure is shown in Figure 8. An unbinned maximum likelihood fit to two Gaussians yields the following parameters: $m_{narrow} = 5703 \pm 14$ MeV/c^2, $\sigma_{narrow} = 28^{+18}_{-14}$ MeV/c^2, $m_{wide} = 5585^{+79}_{-34}$ MeV/c^2, $\sigma_{wide} = 42^{+43}_{-17}$ MeV/c^2,
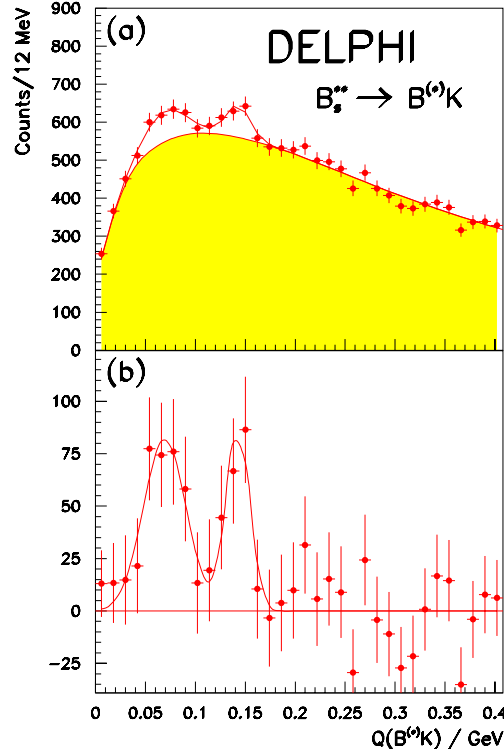
Fig. 6. (a) The distribution of the Q value of inclusively reconstructed B hadrons and kaons observed by DELPHI. The points are the data, and the shaded area is the predicted distribution from Monte Carlo simulation that does not contain B^{**}; (b) the resulting distribution when the predicted background from Monte Carlo is subtracted from the data; the fit is described in the text.

and the total signal is 54^{+15}_{-14}. The value of m_{narrow} and the observed production ratio $\frac{B(Z\to b\to B^{**}_{u,d})}{B(Z\to b\to B_{u,d})} = (30 \pm 8)\%$ are consistent with the values measured using inclusive B reconstruction. The mass resolution using exclusive B decays is 2 to 5 MeV/c^2, almost an order of magnitude better that the resolution achieved with inclusive B reconstruction.

3.6. Results on Flavour Tagging

ALEPH has used their exclusive B sample, and OPAL has used their inclusive B^- sample to measure flavour tagging using the B^{**} resonance and associated fragmentation production. The effectiveness of a flavour tag may be quantified by the product

$$\mathcal{E} = \varepsilon \cdot (1 - 2w)^2,$$

where ε is the efficiency of the flavour tag, and w is the probability that the flavour assignment is incorrect (the mistag probability); $\mathcal{E}$ is bounded between 0 and 1. The

Table 17. Summary of results on Σ_b and Σ_b^* reported[66] by DELPHI. The data sample is 2.3×10^6 hadronic Z^0 decays collected during 1991–1994. The parameters from fitting the two observed enhancements with Gaussians are reported. The widths of the Gaussians were fixed to the expected experimental resolution of 10 and 16 MeV/c^2. The production ratio is defined as $\frac{B(Z \to b \to \Sigma_b^{(*)})}{B(Z \to b)}$. The mass difference with the Λ_b is obtained by adding the mass of the charged pion to the measured Q value. For all reported measurements, the first error is statistical and the second error is systematic.

Excited B Baryon	Σ_b	Σ_b^*
Signal	$937 \pm 108 \pm 270$	
Q (MeV/c^2)	$33 \pm 3 \pm 8$	$89 \pm 3 \pm 8$
$\frac{\sigma(\Sigma_b)}{\sigma(\Sigma_b)+\sigma(\Sigma_b^*)}$ (%)	$24 \pm 6 \pm 10$	
Prod. ratio (%)	$4.8 \pm 0.6 \pm 1.5$	
$M(\Sigma_b) - M(\Lambda_b)$ (MeV/c^2)	$173 \pm 3 \pm 8$	$229 \pm 3 \pm 8$

error on an asymmetry A measured with N decays using a flavour tag of quality $\mathcal{E}$ is

$$\delta A = \sqrt{\frac{1-A^2}{\mathcal{E} \cdot N}};$$

in other words, the equivalent statistics are reduced from N to $\mathcal{E} \cdot N$. Combining their samples of neutral and charged B mesons, ALEPH measures[69] $\mathcal{E} = 15 \pm 4\%$. Using their sample of inclusively reconstructed charged B mesons and requiring the helicity angle of the pion satisfy $\cos \alpha_\pi > -0.7$, OPAL measures[59] $\mathcal{E} = 6.6 \pm 1.0\%$ when they restrict the mass of the $B\pi$ system to lie between $5.60 < m_{B\pi} < 5.85$ GeV/c^2, and $\mathcal{E} = 11 \pm 2\%$ when no restriction to the resonant region is applied. These tagging efficiencies compare favourably with other tags, for example, the typical value of $\mathcal{E}$ using the lepton charge from semileptonic decays of the other B produced in the event is $\sim 2\%$ (per lepton type).

4. Summary

A summary of the measured B hadron lifetimes and lifetime-ratios is given in Table 18. The measured values of the ratios $\tau(B^-)/\tau(\bar{B}^0)$ and $\tau(\bar{B}_s^0)/\tau(\bar{B}^0)$ agree with theoretical expectations. The measured value of $\tau(\Lambda_b)/\tau(\bar{B}^0)$ is significantly below theoretical bounds. The possible sources for this discrepancy are listed in reference [3]. Searches for the B_c meson are negative thus far.

Excited B hadrons have been reconstructed using inclusive reconstruction of weakly decaying B hadrons. B^* production rates and polarization are as expected from spin-counting. The predicted p-wave mesons (B^{**}) provide a good qualitative description of the observed resonant structure in the mass distributions of $B\pi$ and BK combinations. Flavour tagging of B^0 using B^{**} and associated non-resonant pion production appears promising. Finally, the observed significant rate of $\Sigma_b^{(*)}$ may be part of the reason that Λ_b baryons are not fully polarized on the Z^0 resonance.

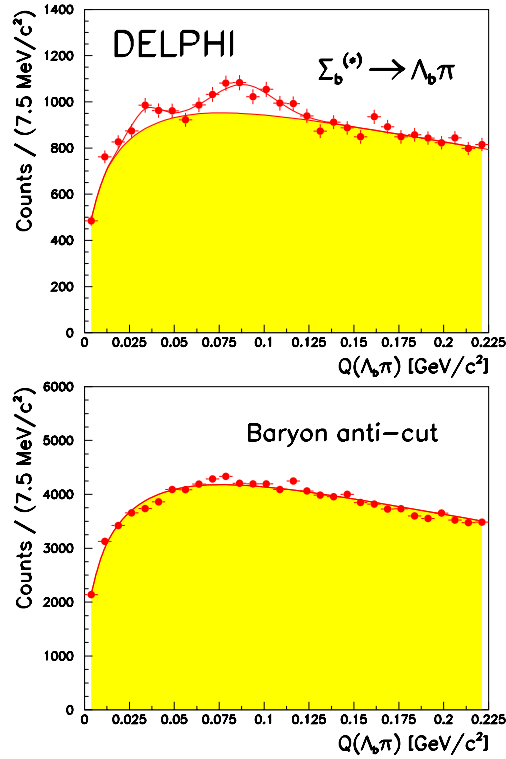The future of these measurements may be summarized as follows:

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Fig. 7. (a) The distribution of Q for inclusively reconstructed B hadrons and pions in a baryon enriched data sample from DELPHI. The points are the data, and the shaded region is the expected background. The curve is the result of a fit to the expected background shape and two Gaussians with widths fixed to the predicted experimental resolution. (b) The same distribution except the data are depleted in baryons; these data are used to determine the background in (a).

- *LEP* – 1995 is the last year on the Z^0 resonance before the energy upgrade. Each experiment will increase its data sample of hadronic Z^0 decays by at most 10^6, yielding total hadronic samples of $4 - 4.5 \times 10^6$ per experiment. Except for specific analyses (*e.g.* those exploiting the RICH detector at DELPHI), adding the 1995 data sample to the results submitted to this conference with not change the statistical errors dramatically. Refinements of the analyses and the addition of further decay channels will lead to further reduction of statistical and systematic errors.

- *SLD* – from 1996 to 1998, the SLC is expected to deliver approximately 5×10^5 hadronic Z^0 decays with 80% electron polarization. This will triple the current SLD data sample. This increase in statistics, along with a new CCD vertex detector with increased solid angle coverage should lead to significant improvements in the measurements from SLD.

- *CDF* – the results submitted to this conference came from either Run 1a (20 pb^{-1} taken during 1992–1993) or from Run 1a and part of Run 1b (70 pb^{-1}). Run 1b started in January 1994 and is expected to end in Spring of 1996.
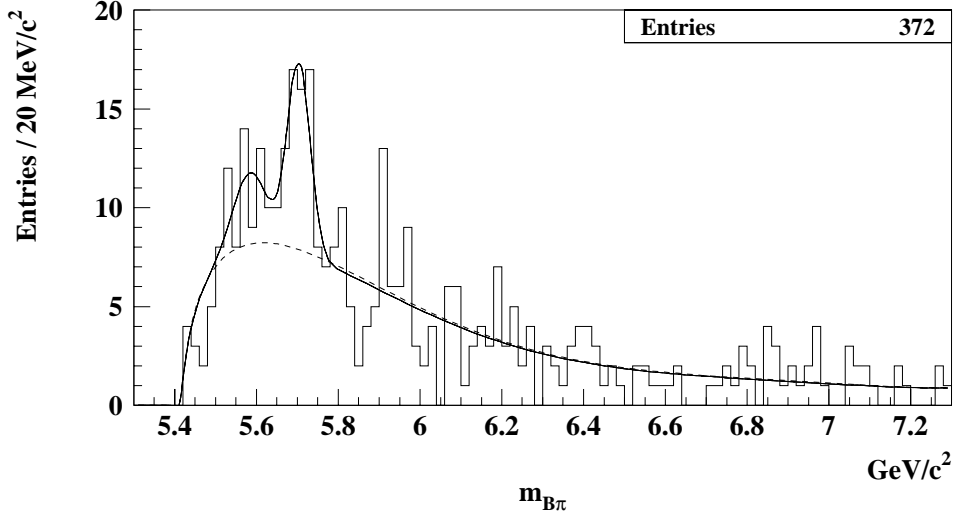
28

Fig. 8. The observed resonant structure of right-sign $B\pi$ combinations, using exclusively reconstructed B mesons in the ALEPH detector. The data are the histogram; the dashed curve is the expected background; and the solid curve is the combination of the background and two Gaussians (see text for fitted parameters) used to describe the observed signal.

Table 18. A summary of the average of measured B hadron lifetimes and the ratio of these lifetimes with respect to $\tau(\bar{B}^0)$.

B hadron	lifetime (psec)	ratio
B^-	1.62 ± 0.05	1.02 ± 0.04
$\bar{B}^0$	1.56 ± 0.05	$-$
$\bar{B}^0_s$	$1.55^{+0.11}_{-0.10}$	0.99 ± 0.07
Λ^0_b	1.18 ± 0.07	0.75 ± 0.05

The anticipated size of the recorded data sample of Run 1a and 1b combined is 140 pb^{-1}. The results submitted to this conference will improve after the full statistics are analysed (for example, the statistical error on $\tau(B^-)/\tau(\bar{B}^0)$ should decrease from 0.09 to 0.07), and many new results are anticipated. This fall, CDF has obtained three new preliminary measurements. In addition to the measurement of the Λ_b mass $m(\Lambda_b) = 5623 \pm 5(stat.) \pm 4(syst.)$ MeV/c^2, mentioned previously, the Λ_b lifetime has been measured[70] to be $\tau(\Lambda_b) = 1.33 \pm 0.16(stat.) \pm 0.07(syst.)$ psec using a signal of $197 \pm 25 \, \ell\Lambda_c$ pairs. The increased statistics have been exploited to improve the measurement of the $\bar{B}^0_s$ lifetime using the exclusive decay $\bar{B}^0_s \rightarrow J/\psi\phi$. From a signal of 58 ± 8 decays, they measure[71] $\tau(\bar{B}^0_s) = 1.34^{+0.23+0.05}_{-0.19-0.05}$ psec. During Run II, which is anticipated to start in early 1999, after the main injector in commissioned, the CDF and D0 collaborations should make definitive measurements of the B hadron lifetimes and lifetime ratios using fully reconstructed decays.

5. Acknowledgements

6. References

In this list, "contribution to this Symposium" means a contribution submitted to the XVII International Symposium on Lepton–Photon Interactions, Beijing, 10–15 August 1995. If an EPS number follows, this number refers to the contribution submitted to The International Europhysics Conference on High Energy Physics, Brussels, 27 July 1995 to 2 August 1995.

1. T. Skwarnicki, *Decays of b Quark*, talk presented at the XVII International Symposium on Lepton–Photon Interactions, Beijing, 10–15 August 1995, to appear in these proceedings.
2. S. L. Wu, *Recent Results on B Meson Oscillations*, talk presented at the XVII International Symposium on Lepton–Photon Interactions, Beijing, 10–15 August 1995, to appear in these proceedings.
3. M. Neubert, *Heavy Flavour Physics*, talk presented at the XVII International Symposium on Lepton–Photon Interactions, Beijing, 10–15 August 1995, to appear in these proceedings.
4. I. I. Bigi, *The QCD Perspective on Lifetimes of Heavy Flavor Hadrons*, UND–HEP–95–BIG02.
5. P. B. Renton, *Review of Experimental Results on Precision Tests of Electroweak Theories*, talk presented at the XVII International Symposium on Lepton–Photon Interactions, Beijing, 10–15 August 1995, to appear in these

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